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Sustainable energy: A review of gasification technologies

Emanuele Graciosa Pereira [a,*], Jadir Nogueira da Silva [a], Jofran L. de Oliveira [b], Cássio S. Machado [a]

[a] Federal University of Vicosa—Department of Agricultural Engineering DEA/UFV, Av. P.H. Rolfs s/n Campus Universitario, 36570-000 Vicosa, MG, Brazil
[b] UFMT—Campus de Rondonopolis—Rodovia Rondonopolis-Guiratinga, KM 06 (MT-270) - Bairro Sagrada Família 78735-910 Rondonopolis, MT, Brazil

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Biomass has been widely recognized as a clean and renewable energy source, with increasing potential to replace conventional fossil fuels in the energy market. The abundance of biomass ranks it as the third energy resource after oil and coal. The reduction of imported forms of energy, and the conservation of the limited supply of fossil fuels, depends upon the utilization of all other available fuel energy sources. Energy conversion systems based on the use of biomass are of particular interest to scientists because of their potential to reduce global CO_2 emissions. With these considerations, gasification methods come to the forefront of biomass-to-energy conversions for a number of reasons. Primarily, gasification is more advantageous because of the conversion of biomass into a combustible gas, making it a more efficient process than other thermochemical processes. Biomass gasification has been studied widely as an efficient and sustainable technology for the generation of heat, production of hydrogen and ethanol, and power generation. Renewable energy can have a significant positive impact for developing countries. In rural areas, particularly in remote locations, transmission and distribution of energy generated from fossil fuels can be difficult and expensive, a challenge that renewable energy can attempt to correct by facilitating economic and social development in communities. This paper aims to take stock of the latest technologies for gasification.

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* Corresponding author. Tel.: +55 31 88533039; fax: +55 31 38992735.
E-mail address: manugraciosa@yahoo.com.br (E.G. Pereira).

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1. Introduction

After a little over 100 years of biomass dominance as fuel, it started to lose its historical leadership to mineral coal energy. As consequence of the continuous growth in the use of oil and natural gas, biomass use today has been reduced practically to homes in rural areas [1]. The worldwide increase in energy demands, however, has resulted in dependency on the increase of fossil fuels, triggering an urgent search for a sustainable solution. In this context, biomass has been an efficient and very attractive alternative. The use of biomass causes a lower emission of greenhouse gases compared to fossil fuels, an advantage which is key for the dissemination of this energy source, since environmental concern is one of the pillars of the sustainability that is so sought after worldwide.

Biomass contributed approximately 14% of the world's energy in 1991, the equivalent of around 25 million barrels of oil a day (mboe/day; = 55 EJ) [2]. In many developing countries biomass is the most important energy source, but it also has an important role in certain industrialized countries. Biomass currently supplies 11% of the total energy consumption of Austria and 17% of the national energy supplies in Sweden [3]. In the United States, the current biomass energy consumption is 4% (200 million dry tons) of total primary energy consumption [4].

The United Kingdom makes significant use biomass, estimated in 2008 at 20 million annual tons. Only a fraction of that is effectively used for the production of energy, though, contributing approximately 4.1% of the heat and electricity production in the country [5].

In Brazil the internal supply of energy in 2006 was 226 millions of tonnes of oil equivalent (toe), or 1.12 toe per inhabitant. Renewable energy sources were responsible for 45.1% of this total, of which 14.8% came from hydrothermal sources and 27.2% from biomass. The total installed power in 2008 was 96.63 GW, of which 4.74 GW, or 4.9%, corresponded to the use of biomass energy [6].

India is the world's largest producer of solar energy systems for rural dwellings and of gasification of biomass. India has reached 70 MW from small-scale biomass gasification systems for the generation of electricity in rural areas. Nowadays biomass fulfills 70% of the basic energy needs in these rural areas, which cover almost 70% of India's population [7].

Biomass and biofuels can be used as substitutes for fossil fuels in generating heat, electricity, and creating chemical products, bringing benefits such as sustainability, regional economic development, social and agricultural development, a regular supply of energy, reduction in the greenhouse gas emissions, and consequently their mitigation [8]. Through energy thermochemical conversion, biomass can be used through three different processes: gasification, pyrolysis, and direct combustion, with gasification being the most efficient processes [9]. Gasification is the conversion of biomass, or any solid fuel, into an energetic gas through partial oxidation at elevated temperatures. This gas, called synthesis gas, constitutes a mixture of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), small quantities of other light hydrocarbons (C_nH_m), carbon dioxide (CO_2), and steam (H_2O), besides the nitrogen (N_2) present in the air and supplied for the reaction. Due to the process, it also results in variable quantities of coal, pyroligneous acids, and tars [10]. The formation of tar is one of the biggest problems faced during the gasification of biomass. Tar condensates under reduced temperatures, polymerizing itself in equipment such as engines and turbines [11].

The conversion efficiency of biomass depends on the use, material, size and shape of the particles, gas flow, and types of reactors, among other factors. Generally, gasifiers can be classified based on the flow direction of the gases: drown draft (co-current), up draft (counter-current), cross draft, and fluidized bed. For using the gas in engines and turbines, the concurrent configuration is the most adequate due to a relatively lower production of tar [12].

Gasification has been attracting worldwide attention due to its varied uses and benefits. Many agricultural and industrial residues that are currently world problems, especially in industrialized countries, can be used in a sustainable way through gasification. From an economical and environmental perspective, the production of hydrogen and ethanol from plastic residues are promising technologies that have been obtaining good results. Another type of residue that can also be used to produce hydrogen from gasification is leftover meat and bones. Such wastes were widely used in the past in the production of feed for bovines; however, after they were found responsible for the propagation of diseases in bovines, their use was suspended. Now gasification represents an alternative way to process these animal wastes, both destroying any disease-causing agents and yielding energy.

The generation of electricity from gasification has been used in several parts of the world for the reduction of greenhouse gas emissions as well as for the supply of electricity in rural areas.

The development of rural areas through renewable energy is possible provided there are adequate financial incentives, subsidies, and reinforcement of the infrastructure in order to guarantee reliability, quality, and efficiency [7].

Biomass gasification technologies can be used for several purposes, such as a source of heat energy, but investments in research and development have been small, and the technologies have not been well enough investigated and publicized. Hence, this article has the objective of surveying the current applications of gasification technology.

2. The process of biomass gasification

The gasification process consists of the thermochemical conversion of carbonaceous material into fuel gas rich in CO and H_2, called syngas. The composition of syngas is affected by gasification conditions, such as temperature, equivalent ratio, and pressure [13].

Providing a valid theory to describe the whole process of gasification in general is very complex due to the variety of raw material available. However, the phenomenon of pyrolysis followed by volatilization of the remaining carbon is predominant in all processes of gasification, leading authors to develop a theory for gasification based on the simplest model of pure carbon, discussing the influence of specific characteristics of different kinds of biomass [14,15].

In discussing the mechanism of any chemical reaction, it is necessary to examine its thermodynamics, that is, the state of specific pressure and temperature conditions in which the process will take place, the kinetics of the process, and the adopted chemical pathway.

3. The state of the art of gasification technologies

The production of energy through biomass gasification might seem like a recent technology, but in reality it has over 100 years of existence. History clearly shows that our forefathers were experts in using fire from the existing biomass. Time and cultural evolution led people to use such elements in new activities requiring high heat, such as pottery and metallurgy. Gradually, techniques for converting biomass into biofuel or directly into energy by means of direct combustion were developed and

modernized in processes that are useful and efficient. The first reported use of gasification happened in 1812 for the lighting of London. A gasification method designed by Bishoff in 1839, and modified by Siemens in 1857, was used for one century. One of its problems, however, was the production of tar. To avert this, products that would promote the "cracking" of the tar were introduced into the reaction zone. During both world wars, when oil was scarce in most common applications due to its largely being restricted for military purposes, work related to thermal conversion using biomass was stimulated. After WWII, however, biomass research was forgotten for some time due to the low prices of fossil fuels. With the news of the depletion of oil wells and natural gas in recent decades, however, along with the growth in costs of fossil fuels and the concerns with the emission of pollutant gases, research activities in thermal conversion of biomass have been stimulated.

3.1. Process Challenges

The gasification process, although old, still requires optimization to minimize the energy efficiency loss stemming from a few main problems: biomass must be dried before conversion; expensive equipment is required to free the synthesis gas from contaminants, then further prevent pollution during combustion; and despite special equipment and treatments, tar is still a part of the synthesis gas.

3.1.1. Tar

The formation of tar is one of the biggest problems faced during the several methods of biomass gasification. The tars formed during gasification consist of a variable mixture of condensable hydrocarbons, with or without other oxygen-containing hydrocarbons and more complex polycyclic aromatic hydrocarbons [16]. Li and Suzuki [17] have reviewed tar's physical and chemical properties and have indicated that the control and conversion of tar is a key issue for a successful application of gas derived from biomass.

Tar formation causes catalyst deactivation, operation interruption, and the production of carcinogenic elements [18].

Tar condenses under reduced temperatures, polymerizing in such equipment as engines and turbines. Tar removal technologies can be divided into two categories: internal treatment in the gasifier (primary methods) and cleansing the heated gas after gasification (secondary methods). Despite the proven effectiveness of secondary methods, primary methods of tar removal have caught the most attention, since they would eliminate the need for cleansing the gas. In a primary treatment, gasification is optimized to produce a gas with the minimum concentration of tar as possible. Primary methods can involve such factors as (1) selection of specific operational parameters, (2) the use of catalysts in the bed, and (3) modification of the gasifier. Operational parameters such as the temperature, gasifying agent, equivalence ratio, and residence time are of extreme importance for the formation and decomposition of tar.

Sun et al. [19] conducted experimental research on rice husk gasification, and one of the studied parameters was the effect of secondary circulating air on the quantity of tar in the synthesis gas. The results obtained show that the quantity of tar is mainly a function of the gasification temperature, decreasing when the temperature of the gasifier is increasing.

Michel et al. [16] used a fluidized bed reactor to study the effects of temperature on tar removal. At 815 °C the fractions (F1 and F2) of tar extracted were 1.41 g and 0.4 g. For the highest temperature (880 °C) only one fraction of 0.2 g was obtained and fraction F1 was negligible. Min et al. [20] showed that the tar yield of mallee wood decreased with increasing temperature due to increased thermal cracking. However, a different trend was found by Meng et al. [3] who observed that at a higher temperature (780 °C), the tar content was higher. This may be explained by the fact that total tar content produced from biomass gasification depends not only on temperature, but on other parameters as well.

Many chemical substances have been proposed to enhance tar removal. According to Mohammed et al. [21] three main groups of catalysts can be used: (1) naturally occurring catalysts such as dolomite and olivine; (2) alkali metals such as KOH, K_2CO_3, $KHCO_3$, Na_2CO_3, $CaCO_3$, $CsCO_3$, KCl, $ZnCl_2$ and NaCl; and (3) nickel-based catalysts, which have been evaluated for tar reduction in syngas. Nickel-based catalysts are reported to be very effective not only in reducing tar, but also in decreasing the quantity of nitrogenated compounds such as ammonia. Although this provides satisfactory catalytic activity, nickel-based catalysts are expensive, easily deactivated and poisonous at high temperature.

Natural dolomite is the most popular catalyst since it is easily available, inexpensive, disposable and can significantly reduce the tar content of the syngas. A major problem with using dolomite is its deactivation due to the quick calcination in the gasifier. Dolomite is a soft and fragile material that erodes easily, generating a raw gas with a high particulate content. Olivine is mechanically stronger than dolomite. Corella et al. [22] reported that although olivine was shown to be 1.40 times less effective for in-bed tar removal than raw dolomite, it generated four to six times fewer particulates in the gasification gas than dolomite. To increase the tar elimination activity of natural olivine, Michel et al. [23] investigated the gasification of Miscanthus *X* Giganteus in a fluidised bed reactor with the presence of Ni/olivine based catalysts. The results showed that the addition of NiO to the olivine catalyst was efficient for reducing tar. Rapagnà et al. [24] carried out steam gasification of biomass in a fluidized bed reactor using a 10 wt% Fe/olivine catalyst and found that the studied catalysts reduced naphthalene and toluene by 48% and 59%, respectively.

Skoulou [25], gasifying olive kernel with high-temperature steam, analyzed the characteristics of the process and its product. Olive kernel contains, among other metals, Fe. In reactions with the gasifier's high-temperature steam, Fe seems to act as a catalyst to destroy tars.

González et al. [26] investigated the effectiveness of dolomite during the two-stage gasification processes of olive cake and found that dolomite is an effective catalyst for cracking heavy hydrocarbons. Kim et al. [27] gasified plastics using a two-stage gasifier to examine the effects of activated carbon and dolomite on tar removal. Activated carbon was more efficient at tar removal than dolomite. The use of activated carbon decreased total tar production by 2.5 times and increased H_2 production by a factor of two. Bassil et al. [28] investigated a method to eliminate tar with solvents such as methyl hexadecanoate and paraxylene, resulting in a database to dimension the tar extraction unit of the biomass conversion process. Kirnbauer et al. [29] studied the positive effects of bed material coating on tar reduction in a dual fluidized bed gasifier. They found that the positive effect was caused by the formation of a calcium-rich layer on the used bed material as a result of the interaction of bed material (olivine) with biomass ash and additives. The catalytic properties of used bed materials led to an approximately 80% decrease in tar content. Barman et al. [30] proposed a realistic gasification model with a representative composition of tar along with other components in the produced syngas. The study considered tar composition and tar yield of 4.5% (mass percentage), the same value reported by Yamazaki et al. [31], as input parameters in the

model. Granovskii et al. [32] injected acetylene and hydrogen flames into the blend of gases containing toluene (model tar compound) and concluded that the proposed treatment converted toluene to H_2 and CO due to both heat supply and interaction with combustion products. An optical method for determining the tar content of the product gas by means of fluorescence spectroscopy has been developed by Baumhakl and Karellas et al. [33]. This method uses optical sources and detectors available for less than €5000 and useful for both laboratory experiments and industrial applications.

3.1.2. Biomass moisture

The moisture content of the biomass affects both the operation of the gasifier and the composition of syngas. Brammer and Bridgwater [34] studied the influence of moisture, before and after drying, on the performance and cost of a gasifier engine for the combined generation of heat and electricity.

The study showed that the presence of excessive moisture in biomass harms the quality of the produced gas and the general performance of the system, since much of the energy is used in the evaporation of the water contained in the biomass. The influence of the moisture content in raw biomass was also investigated by Plis and Wilk [35], who found that the CO content in the syngas is higher in the case of dry fuels, while the CO_2 content increases with the moisture in the feedstock. Additionally, higher moisture content in the biomass reduces the molar fractions of the combustible components and the efficiency of the process. In order to examine the effects of biomass moisture on syngas, Antonopoulos et al. [36] developed a non-stoichiometric model for a downdraft gasifier using olive wood, miscanthus and cardoon. The increase in biomass moisture content decreased the lower heating value (LHV) of the produced gas. A 40% increase in fuel moisture resulted in an approximately 1 MJ/m^3 reduction of the LHV of the synthesis gas.

The moisture content limits for gasifier feedstock rely on the type of gasifier used [37]. The highest moisture content for a downdraft gasifier is generally considered to be 25% wet basis and not higher than 50% for an updraft gasifier.

The need to dry biomass before submitting it to gasification might create great capital and energetic costs in small and medium biomass gasification plants producing heat, electricity and liquid fuels.

Gonzalez et al. [38] analyzed the economics of producing cellulosic ethanol from loblolly pine, natural mixed hardwood, eucalyptus, corn stover, and switchgrass via indirect gasification. They concluded that biomass moisture content was an important economic aspect and lower moisture content in feedstocks led to better financial performance of the thermochemical ethanol conversion process. Reducing the feedstock moisture content from 45 to 35% increased net present value (NPV) by US $66 million and the internal rate of return (IRR) by 2.8 percentage points.

In this context, with the advantage of avoiding costs during the drying process, gasification into supercritical water is a promising technology to convert wet biomass (water content of 70 wt% or more) into gas rich in H_2 and methane. Supercritical water gasification (SCWG) exists at pressures higher than 2.2 Mpa and temperatures above 374 °C (supercritical condition). Under supercritical conditions, the biomass is almost completely gasified and the cleavage products of biomass dissolve in the supercritical water, minimizing the formation of tar and coke. Withag et al. [39] presented a system model for the process of gasification of biomass model compounds in supercritical water. The model was generated in ASPEN 12.1 under the assumption of chemical equilibrium and using model compounds to represent the organics in the wet biomass. The study determined the influence of several parameters on the thermal efficiency of the process.

Lu et al. [40] studied corn cob gasification in SCW with a tubular reactor system and used orthogonal experimental design method to optimize the operation parameters.

Xu et al. [41] investigated the effects of moisture content on supercritical water gasification of the dewatered sludge. The water content varied from 76.2 to 94.4 wt%. Although Xu et al. [41] concluded that it was difficult to fully understand how water content affected the reactions; they observed that increased water content resulted in a decrease in total gas production, but an increase in gas yield. Madenoglu et al. [42] performed a SCWG of five different types of biomass (cauliflower residue, acorn, tomatoes residue, extracted acorn and hazelnut shell), aiming to increase decomposition of biomass with high lignin content into hydrogen and/or methane rich gaseous products using K_2CO_3 and Trona as catalysts. Trona was found to be as effective as K_2CO_3 in SCWG of biomass feedstock. The results indicated that the use of K_2CO_3 and Trona increased hydrogen yields and enhanced carbon gasification efficiencies.

3.1.3. Secondary equipment

The produced gas from biomass gasification contains lots of impurities which decrease the efficiency of the thermo chemical conversion process. The gas quality is related to the gasifier configuration, the chemical composition of the feedstock, the feedstock's moisture and ash content, the equivalence ratio, and reaction temperature profile.

The greatest challenge for biomass gasification for energy production may be the costliness of secondary, or auxiliary, equipment needed to create clean gas relatively free from contaminants.

This greatly drives up the cost of the entire process, accounting for more than half of the final price of produced biofuel [43]. The need for cleaning syngas depends on the intended use of the gas, being particularly important in cases when syngas will be used to synthesize liquid fuel. In accordance with Gonzalez et al. [38], gas cleanup steps are crucial to preventing both catalyst fouling and poisoning in the subsequent alcohol synthesis steps.

Auxiliary systems are operations supplemental to the basic process of gasification and generally are placed into one of two categories: (1) preparation of the fuel and its insertion in the gasifier, or (2) cleaning the resulting gas.

Secondary methods can be organized in two categories: wet gas and hot gas treatment [44]. Dry gas cleaning is usually applied when the temperature is higher than 500 °C prior to gas cooling and partly below 200 °C after gas cooling. Wet gas cleaning is typically applied at temperatures of about 20–60 °C after the gas cooling. In general, since the gas cooling treatment requires the gasification product gas to be cooled down, a loss of overall thermal efficiency occurs in this process, and creates water residue that must be further treated for disposal [20]. Hot gas cleaning could improve energy efficiency and reduce operating costs for using syngas [45].

Typical equipment for dry gas cleaning are cyclones, baffle filter, bag filter, ceramic filter, candle filter, and separators; with wet gas cleaning using scrubbers, spray towers and wet electrostatic precipitators. Villot et al. [46] demonstrated the feasibility of removing the particles contained in syngas at high temperature (500–1000 °C) and pressure (0.1–1 MPa) with an electrostatic precipitator.

Cummer and Brown [43] have collected information on auxiliary systems, giving a better understanding of the whole gasification process. Mondal et al. [47] reviewed syngas cleaning options, including various types of feedstocks and downstream

applications of syngas. They also discussed techno-economic analysis of various gasifiers and syngas cleaning processes.

3.2. The governing parameters in the gasification process that affect the produced gas

During biomass gasification, several parameters, such as temperature, gasifying agent, biomass fuel properties, particle size, operating pressure, equivalence ratio, catalyst addition and gasifier type, have substantial influence on the product yields and syngas composition. For a specific gasifier design, there are two major parameters which are used to maintain an acceptable syngas quality level: the equivalence ratio and the gasification temperature. A high reaction temperature provides a high gas flow and increases the yield of hydrogen and syngas. Michel et al. [23] investigated the effects of temperature (815–880 °C) on the yields and the compositions of syngas and tars in a fluidized bed reactor with the use of olivine as catalyst. The results showed that yields of tar, char, CO, CO_2 and CH_4 concentrations decrease with temperature, while the gas yields and the content of H_2 increase. At 880 °C, the CO content was 24.35% and for H_2 it was 45.89%. Tremel et al. [48] also showed a large influence of temperature and pressure on the gasification of Rhenish lignite. In entrained flow gasification, experiments were conducted at atmospheric pressure and at 0.5 MPa. At both pressures, coal conversion increased with temperature and residence time. The highest conversion of 96 wt% was achieved at a particle residence time of 1.3 s, at a temperature of 1600 °C, and a pressure of 0.5 MPa. Studying the effect of temperature on gasification of pine sawdust, Xie et al. [49] obtained syngas with a maximum yield of 3.29 $Nm^3\,kg^{-1}$ biomass at 850 °C. The gasification air ratio is defined as the amount of oxygen fed into the gasifier divided by the amount of oxygen needed for complete combustion. The equivalent ratio (ER) is important in designing the parameters of a gasifier. According to Chang et al. [50], a higher equivalent ratio provides lower yields of hydrogen, syngas and gas low heating value. This is because a reaction with a higher equivalent ratio favors complete combustion. Typical values of *ER* for biomass gasification vary between 0.2 and 0.4. Son et al. [51] studied gasification of wood utilizing a downdraft gasifier at air ratio around 0.3–0.35 and obtained a low heating value of 1100–1200 kcal Nm^{-3} and cold gas efficiency of 69–72%. Seggiani et al. [37] examined the impact of the ER in an experimental updraft gasifier fed by sewage sludge with woody biomass under various operating conditions. They identified that an ER value of 0.25 gave the best performance of the updraft gasifier and therefore higher fuel gas production.

Employing a downdraft fixed bed gasifier, Gai and Dong [52] investigated gasification of corn straw under atmospheric pressure, using air as an oxidizer. It was observed that the rise in ER from 0.18 to 0.32 decreased the mole fraction of CO_2 from 23.93 to 11.58%, while CO increased from 11.35 to 19.81%. The mole fraction of H_2 concentration was also observed to increase from 6.91 to 13.51%. Different trends were observed by Thanapal et al. [53] during gasification of dairy biomass with enriched air mixture using a fixed bed gasification facility. With increased ER, carbon dioxide increased and carbon monoxide decreased. Additionally, the higher heating value (HHV) of the gases decreased with an increase in the equivalence ratio (decrease in oxygen concentration). Similarly, Tanigaki et al. [54] analyzed the effects of the equivalent ratio on syngas composition from co-gasification of municipal solid waste. They concluded that although higher ER has a positive influence on tar yield due to higher gas temperature, it is not satisfactory for flue gas cleaning. In their experiments, the CO concentration in syngas tended to decrease while ER increased, which could result in incomplete combustion in the combustion chamber due to a low LHV of syngas. In addition, carbon conversion ratio was increased with the equivalence ratio while char yield was decreased. In accordance with Martinez et al. [55], another parameter that affects the quality of syngas is superficial velocity (*SV*), defined as gas flow rate divided by the internal cross section of the gasifier. Low SV values lead to a slow pyrolysis process with high yields of char and significant amounts of unburned tars. Although high values of *SV* promote low char formation, such high *SV* values result in lower residence time inside the gasifier, reducing the efficiency in the tar cracking processes. A superficial velocity which increases with airflow rate is independent of gasifier size and allows for the comparison of gasifiers of different dimensions [31]. Sharma et al. [56] presented an experimental study to obtain fluid flow characteristics of a suction gasifier (downdraft) system using kiker wood as feedstock. In their experiments, higher gas flow rate resulted in better system performance. This is explained by the fact that the increase in the air/biomass consumption ratio in the final gas caused by higher flow rates increases oxidizer (air) to increase further oxidation, resulting in increased reaction temperature. Better conversion of non-combustibles component (viz., CO_2, H_2O) into combustible components (viz., CO, H_2) is then obtained with higher reaction temperature or calorific value. Higher calorific value with less consumption of biomass results in better gasification efficiency.

The influence of catalysts on gasification performance was demonstrated by Chiang et al. [57] who investigated the influence of the mineral catalyst (CaO) on gasification of paper-reject sludge. The results showed that at 600 °C the use of 20% of CaO resulted in an increase of lower heating value from 10.6 MJ/Nm^3 to 13.04 MJ/Nm^3. However, for high temperatures (900 °C) the catalyst effect on the increased energy content of synthesis gases was insignificant. The CO_2 absorption by CaO is dependent on the partial pressure of CO_2 in the syngas at the specified temperature. When the gasification temperature is higher than the equilibrium temperature, $CaCO_3$ will desorbs to produce the tested catalyst CaO, thus not increasing the lower heating value of synthesis gas. The effects of biomass fuel properties on syngas were shown by Cascarosa et al. [58], who evaluated the co-gasification of low percentages of meat and bone meal (MBM) with coal in a fluidized bed. At high temperature (900 °C) and ER (0.35), the substitution of 1 wt% of the coal used in this gasification process by MBM caused a 21% increase in gas yield. However, the gas lower heating value decreases around 35.7% with the addition of 1% of MBM at the same operating conditions.

3.3. Applications of gasification technology

Gasification is currently a very active area in work developing biomass as fuel. There are ongoing projects seeking sustainable gasification systems for the generation of several forms of energy.

3.3.1. Electrical energy generation

Generating electrical energy from gasified biomass has long been used worldwide. Hence, considerable research has been conducted over the last twenty years with the purpose of advancing gasification technology and to adapt it to applications with biomass. Beenackers [59] presented a review of the most used technologies for biomass gasification in Europe at the end of the 1990 s, indicating a special interest in the combination of generating both heat and electricity.

In Brazil, the project GASEIFAMAZ called Comparison between the Existing Technologies for the Gasification of Biomass was a partnership between the National Biomass Center (CENBIO), the Biomass Users Network of Brazil (BUN), and the Institute of

Technological Research of the State of São Paulo (IPT) and University of Amazonas (UA). This project's main objective was to evaluate the Indian technology of gasification in fixed beds for small-scale use, seeking the supply of electricity in a sustainable manner to isolated communities in the Amazon region. A gasification system of 20 kW was imported from the India Technological Institute. During tests a calorific value of 5.7 MJ/Nm^3 was obtained, for a biomass consumption of 18 kgh^{-1}.

This gasification system was installed in the community of Aquidabam, part of the town of Manacaparú, in the state of Amazonas. The community has 180 houses and 700 inhabitants. One of its local products is cupuaçu, a fruit found in the Amazon region, sold "in natura" with a low aggregated value. The gasification system ws installed with hopes to accelerate the formation of a local agro-industry for the commercialization of the cupuaçu's pulp, which will enable an increase in the community's income and consequently an increase in the residents' quality of life [60].

One of the most successful plants of biomass gasification is installed in Austria in the village of Güssing. A gasifier in a rotating fluidized bed produces around 2.0 MW of electrical energy and 4.5 MW of thermal energy. The gas is used, after being cleaned in a gas-run engine associated with a boiler, for the combined production of heat and power; this association is also known simply as combined heat and power (CHP). In the process of gasification with an internal combustion engine (IC) the biomass is gasified, and electrical energy is produced in a generator attached to the IC engine. Before the combustion, though, the gas goes through a treatment system of cyclone, filter, and cooling [61].

Berggren et al. [62] investigated the energy potential of biomass and coal gasification in the Polish energy generation system. The results showed a potential power production from 2.3 to 6.6 TWhe, which represents 1.6 to 4.6% of Poland's total electricity production in 2010. The implementation cost of this energy strategy would be well under 20 euro per MWhe, much less than the average price of 96 euro per MWhe in 2003.

Bridgwater [63] has assessed the technologies and economics of integrated systems producing electricity from several types of biomass—in particular, wood. The review considered all the necessary elements, such as management, preparation, processing, and gas cleaning. The results showed the biomass gasification technology already at an advanced level, justifying the implementation of the *integrated generation with combined cycle* (IGCC) concept.

The cleansing of the gas, the less-developed aspect under consideration, is where most of the problems are. Brown et al. [64] conducted a thermal-economical study of an industrial wood gasification plant with a capacity of 20 MW, contemplating both the cleaning of the gas and energy conversion. Two setups were tested: an internal combustion engine–combined cycle (ICE–CC) and a gas turbine–combined cycle (GT–CC). The operational conditions that maximize the efficiency of the ICE–CC are also those that minimize formation of tar. For the GT–CC setup, the tar concentration was bigger, although not to be considered a big problem, since the cleansing of the hot gas can effectively prevent the condensation of tar.

Sharma [12] conducted an experimental study on a biomass gasifier with concurrent flow with a power of 75 kW_{th}. The temperature profile obtained increases as long as there is an increase in the airflow rate through the bed of the gasifier. The results also show that the highest temperature is maintained near the oxidation zone. The highest bed temperature increases from 1115 K to 1168 K, when the airflow speed increases from 7 g/s to 9 g/s. Henriksen et al. [65] conducted a study in a gasifier of the same power, 75 kW, although this was a two-stage gasifier. During the tests it ran automatically day and night for over 2,000 hours, and only adjustments in the feed systems were necessary. The gas-cleansing system of a sleeved filter worked wonderfully. Engine operation was satisfactory with the filtered synthesis gas, and no buildup was noticed. Small quantities of buildups containing salts and carbonates were seen in the heat changer, though.

Kersten et al. [66] have described a multiphase gasification system with a circulating fluidized bed reactor. The benefits of this concept, in which different processes are conducted separately in the different parts of the same reactor, has been demonstrated for specific types of biomass, showing that is possible to create oxidation zones in which the O_2 reacts exclusively with the carbon. This creates better conversion and consequently greater efficiency.

Leung et al. [67] reviewed the technological development of biomass gasification for a variety of applications in China and discussed its scenarios. Biomass gasification for the purpose of electrical energy generation is very promising, possessing great potential in research and development in China.

López et al. [68] reported on using biomass for electrical energy generation, with the specific investigation into finding a better location for the industrial project with three alternative technologies: gas engine, gas turbine, and fuel cells with micro-turbines. The study took into consideration such variables as the biomass distribution location, transportation costs, and distance from the existing electrical energy distribution network.

Mathieu and Dubuisson [69] presented an original model of a biomass gasification process, with particular application to wood gasification. The model, based on minimization of the Gibbs free energy, was evaluated in the Aspen Plus process simulator. It was concluded that for the gasifier studied, there is a critical air temperature, above which preheating is no longer efficient. There is an optimal oxygen factor, also, and pressure increase brings little increase in the process's efficiency. Polyzakis et al. [70] optimized a *combined-cycle power plant* (CCPP) system, describing and comparing four different cycles: simple cycle, cycle with internal cooling, reheated cycle, and cycle with internal cooling and reheated. The proposed system is theoretically capable of generating 300 MW of energy (200 MW coming from a gas turbine, and 100 MW from a steam turbine). The results showed that the reheated cycle with gas turbine obtained the best results, especially due to the gas's high temperature exhausted by the turbine, resulting high thermal efficiency in the steam cycle.

The integration of evaporative gas turbine cycles (*evaporative gas turbine cycle*, EvGT) with biomass gasification is an interesting technology that should be able to sustain a large future demand. Steinwall [71] developed and evaluated systems and showed that this integration is thermodynamically viable, with an electric efficiency between 38% and 45% (LHV). The total efficiency for the modeled systems varies from 84% to 92% for a cogeneration system.

3.3.2. Heat generation

Biomass gasification is one of the most suitable processes for Combined Heat and Power (CHP), being a direct route to extract energy from renewable resources efficiently. According to Ahrenfeldt et al. [72], the combination of biomass gasification and a gas engine for heat and power purposes is a promising technology for small-scale plants and has high biomass to power efficiency potential (35–40%) compared to conventional technology. Employing a fixed bed gasifier with a compact cogeneration system to cover electrical and thermal demands in a rural area, Coronado et al. [73] obtained global system efficiency of 51.42%. Damartzis et al. [74] investigated a Combined Heat and Power

(CHP) biomass bubbling fluidized bed gasification unit coupled with an internal combustion engine (ICE) by using a comprehensive mathematical model based on the Aspen Plus® process simulator. The assessment showed that maximum syngas yield was obtained at $T=750$ °C and ER=0.2. Pelegrini and Junior et al. [75] reported that a cogeneration system is an alternative for ethanol plant for production of sugar, ethanol, electricity and heat from sugar cane.

Silva et al. [76] studied the viability of a gasifier/combustor that uses eucalyptus logs, sawmill residues, wood shavings, and corncobs as fuel in the drying of agricultural products. A gasifier developed earlier by Silva [77] was used, with modifications made to the gasification chamber: (1) reduced grill area from 0.21 to 0.06 m^2; (2) addition of a coating involving the superior part of the gasifier; and (3) a butterfly valve at the exit of the combustion chamber. It was concluded that the gasifier using of eucalyptus shavings as fuel consumed between 15.3 and 18.8 kg h^{-1} of biomass, in which the equipment was feasible for the drying of depulped coffee and for other agricultural products, with no impregnation of smoke or other particles.

The use of biomass gasification reactors attached to gas combustors is also an alternative that is energy efficient and functional for the heating of poultry houses. It is hypothesized that this technology might present to the poultry farmer a reduction in production costs, in comparison to the traditional heating systems for poultry houses [78].

Dudynski et al. [79] studied gasification of waste feathers in a fixed-bed gasifier for heat production. With this technology it was possible to utilize 10,000 t of feathers per year and produce 2500 m^3 of syngas from one ton of feathers, resulting in 25 million cubic meters of syngas, or more than 100,000 GJ of heat per year. Pa et al. [80] used the Life Cycle approach to investigate the replacement of natural gas combustion for district heating by wood waste and wood pellets gasification systems with or without emission control. Controlled gasification can reduce external costs by 35% and GHG emission by 82%. Wood pellets have shown to be a better option than wood waste since it needs less primary energy and has much lower impact on the local air quality. Kaliya et al. [81] also conducted a life-cycle assessment for corn ethanol compared to gasoline by replacing fossil fuels with different biomass fuels (corn stover, dried distillers grains with solubles (DDGS), and sirup (solubles portion of DDGS). The biomass conversion technologies/systems considered by Kaliyan et al. [81] were process heat (PH) only systems, combined heat and power (CHP) systems, and biomass integrated gasification combined cycle (BIGCC) systems. The life-cycle GHG emission reduction for corn ethanol compared to gasoline was 119.0% for BIGCC with corn stover, and 111.4% for BIGCC with sirup and stover.

3.3.3. *Ethanol production*

Producing ethanol from cellulose promises to greatly increase the volume of fuel ethanol that can be produced in the world. Cellulosic ethanol can be obtained from a wide range of biofuel feedstock that reach beyond current crops and the land currently used for food and feed.

According to Xu et al. [82] three major research areas using lignocellulosic biomass for biofuels are (a) enzymatic hydrolysis of cellulose followed by sugar fermentation, (b) gasification followed by raw syngas fermentation, and (c) gasification followed by Fisher-Tropsch catalysis.

The partial combustion of lignocellulosic biomass through gasification breaks complex polymers and converts into synthesis gas. A sustainable alternative for the production of ethanol is then the fermentation of synthesis gas. The syngas-to-ethanol route is not well detailed in the literature, but the U.S. Dept. of Energy has estimated that conversion efficiency is 0.15 $m^3\ t^{-1}$ of feedstock [83]. Several bacteria have been investigated for their use in syngas fermentation for ethanol production.

The anaerobic bacteria *Clostridium ljunduhdi* and *C. autoethanogenum* have demonstrated the production of ethanol and acetic acid from CO, CO_2, and H_2 through the acetogenic process. Cotter et al. [84] used a reactor for the fermentation of synthesis gas and have concluded that the autotrophic bacteria *C. ljungdahlii* and *C. autoethanogenum* are capable of producing measurable quantities of ethanol and significant quantities of acetate with this process.

Bredwell et al. [85] reviewed the progress in the development of gas synthesis fermentation, emphasizing the efforts to increase the transference efficiency of the gas mass. Metabolic properties of many microorganisms capable of fermenting synthesis gas were described.

Younesi et al. [86] conducted experiments in which synthesis gas presented several initial pressures, 0.8–1.8 atm, with intervals of 0.2. The formation of acetate was almost the same for all the initial pressures. The maximum production of acetate (1.3 g l^{-1}) was obtained when the total synthesis gas pressure was equal to 1.4 atm. However, the maximum concentration of ethanol, 0.6 g l^{-1}, occurred with the total synthesis gas pressure at 1.6 and 1.8 atm.

Gonzalez et al. [38] simulated in Aspen Plus an economic evaluation and analysis on the production of cellulosic ethanol using different feedstocks such as loblolly pine, natural mixed hardwood, eucalyptus, corn stover, and switchgrass via indirect gasification. Simulated alcohol yields from forest-based feedstock (loblolly pine, natural hardwood and eucalyptus) were significantly higher than from switchgrass and corn stover. This results in better financial returns when compared to herbaceous energy crops or agriculture residues. It is explained by the fact that forest-based feedstocks present higher %C and %H content and lower %ash, yielding greater alcohol production values. By using an Aspen Plus process model, Kou and Zhao et al. [87] also simulated a thermochemical ethanol plant with capacity of 2000 MT biomass per day located in southwest Indiana. The model investigated economic analysis and predicted yield of ethanol produced from corn stover, wood chips and municipal solid waste. The plant simulated included seven sub-systems: feedstock drying and handling, gasification, syngas conditioning, ethanol synthesis, ethanol separation, steam and electricity generation, and water management. Syngas was synthesized into ethanol in a fixed bed reactor.

3.3.4. *Hydrogen production*

Hydrogen production from biomass gasification is gaining attention for use as a clean energy. There is growing interest in producing hydrogen from alternative raw materials, since the processes that involve fossil fuels are not very viable. Many kinds of feedstock can be gasified for this purpose, including plastic residue [88], wood sawdust [89], meat and bone waste [90], pellets [91], rice husk [92], oil palm waste [93,94].

A key factor in maximizing hydrogen production is the use of catalysts in the gasification process and nickel-based catalysts have been showing efficiency for the reduction of tar and hydrogen production [89,91,95–99].

Wu et al. [89] carried out a steam pyrolysis-gasification of wood sawdust with a Ni/MCM-41 catalyst for hydrogen production in a two-stage fixed bed reaction system. Hydrogen production was increased from 30.1 to 50.6 vol.% when the Ni loading was increased from 5 to 40 wt%.

Ruoppolo et al. [91] studied gasification in a fluidized bed gasifier with and without steam from different pellets (wood, biomass/plastic and olive husks) using an Ni-based catalyst

supported on γ-alumina. The catalysts yielded good results in terms of the hydrogen concentration (up to 32% vol.). Although the presence of steam increased the hydrogen concentration, the presence of the catalyst was more effective in increasing the hydrogen and decreasing tar.

Wu et al. [99] prepared seven types of catalysts in the laboratory to investigate the production of hydrogen from polypropylene gasification in a two-phase reactor system. The results indicated (1) that the catalyst Ni/Al_2O_3 was very efficient in the production of hydrogen, but (2) the catalyst $Ni/CeO_2/Al_2O_3$ did not present high catalytic ability.

Soni et al. [90] studied the meat and bone waste gasification for the production of hydrogen. This process, followed by the thermal cracking of tar, was made in two stages under atmospheric pressure in a fixed-bed reactor. The results showed that these animal residues can be effectively used as an alternative source of gaseous fuels, as well as for the production of hydrogen and synthesis gas. Temperatures higher than 850 °C were seen in both stages, favoring the high production of hydrogen/synthesis gas. There were no significant variations in the gas composition.

Compared to other methods of hydrogen production, gasification techniques remain immature and further research regarding their production and conversion will be necessary for them to become economically feasible. In this context, alternative approaches have been studied, such as Underground Coal Gasification (UCG). UCG is the process of in situ conversion of coal deposits to combustible gaseous products, involving processes of building coal mines, coal exploitation, and above-ground gasification [100,101,102]. Stanczyk et al. [100] showed the feasibility of hydrogen production in the underground gasification of hard coal using a two-stage gasification process in which oxygen and steam were supplied to the reaction zone separately in alternate stages. The average hydrogen concentration during the oxygen stage was 15.28% with a maximum of 54.4%. Hongtao et al. [101] studied two-stage underground coal gasification to improve the caloric value of the syngas. The caloric value of the produced gas reached 10.54 MJ/Nm^3.

Other alternatives for hydrogen production have been tested as well, such as steam gasification [50,92,93,94], supercritical water gasification (SCWG) [103,104,105] and, plasma gasification [106,107]. Chang et al. [50] conducted gasification of agricultural wastes for hydrogen production in a fluidized bed. At the equivalent ratio of 0.27, a temperature of 800 °C and steam to biomass ratio of 1.5, they obtained a hydrogen yield of 15.69% and CO of 7.82%. Karmakar and Datta [92] studied steam gasification of rice husk in a fluidized bed gasifier and found that hydrogen content in product gas had reached as high as 53.08%. Using MATLAB for a parametric study, Inayat [93] conducted process modeling for hydrogen production from oil palm empty fruit bunch (EFB). They found that the temperature had a more significant influence on the hydrogen yield compared to the steam/biomass ratio. Additionally, 76.1 vol% hydrogen was predicted in the product gas at 1023 K and a steam/biomass ratio of 3.0. Although the use of steam has been shown as an effective way to enhance hydrogen yield, the excess amount of the steam in the system decreases hydrogen efficiency as more energy is required to heat up the supplementary steam. Nipattummakul et al. [94] investigated steam gasification of residual branches of oil palm tree and obtained a maximum hydrogen yield of approximately 3.5 g at 700 °C and at a steam flow rate of 3.10 g/min.

Byrd et al. [103] studied hydrogen production by gasification of switchgrass biocrude in supercritical water using several catalysts. In their study, the highest hydrogen yield of all tested catalysts was from Ni/ZrO_2 (0.98 mol H_2/mol C). Cao et al. [104] demonstrated high levels of hydrogen (40.26–61.02%) from SCWG of alkaline wheat straw pulping black liquor in continuous flows system. Lu et al. [105] investigated biomass gasification in supercritical water using concentrated solar energy. The results showed that this technology can achieve high efficiency solar thermal decomposition of water and biomass for hydrogen production.

Kalinci et al. [106] did an exergy analysis on hydrogen and syngas production from plasma gasification of sewage sludge. Byun et al. [107] investigated thermal plasma gasification of waste and showed the feasibility of the production of high purity H_2 (> 99.99%) from this technology.

4. Conclusion

Looking at the characteristics of gasification, as well as the most important technologies and research worldwide, it can be inferred that biomass gasification plays an extremely important role in meeting the future needs of growing regional and world populations with more intense energy requirements. Gasifying biomass residues for energy promises such benefits as sustainability, a balanced reduction of greenhouse gas emissions, regional economic development, social and agricultural development, and a steady energy supply.

Thus, biomass gasification deserves greater attention to be use worldwide as well as for research issues, so there can be further significant advances in gasification technologies.

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